Met Office

Forecasting Research Technical Report 585

Benefit of convective-scale data assimilation and observing systems in the UK Models

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December 2013

Abstract

Experiments to measure and apportion the benefit of the 3DVAR data assimilation system in the 4km 'UK4' model are reported. Three principal versions are compared: a continuous data assimilation (DA) system, a similar configuration omitting those observation types exclusive to the high-resolution UK4 assimilation system, and a baseline 'no high-resolution DA' system in which forecasts begin from a 25km global analysis downscaled to 4km. By configuring our trials in this manner we can distinguish between the impact due to the higher model resolution and that arising from the additional high-resolution observation types.

Results from four representative multi-week trial periods spanning July 2011 to March 2012 show that continuous UK high resolution assimilation yielded overall benefits for three of the four periods, relative to starting from the downscaled global analysis. The detrimental signal for the fourth period was dominated by poor cloud and screen temperature performances over a 5-day stratocumulus episode. The overall benefit can be attributed mainly to assimilating at a higher grid resolution, whereas the contribution from the high-resolution observation types was mixed. Investigation of this mixed impact pointed mainly to problems with cloud assimilation, in which further progress has been made recently.

Similar experiments over one of the trial periods were also undertaken in the 1.5km UKV model. The results indicated that the marginal benefit relative to its downscaler in the higher resolution UKV model may be greater than that found in the UK4. A further trial with no interior data assimilation suggested that the benefit from high-resolution assimilation relative to global assimilation was greater than that conveyed by global assimilation relative to none.

Further observing system experiments were carried out to determine the relative contribution of individual observing networks to the overall performance of the UK4 data assimilation system. The component which delivered the greatest benefit to forecasts of surface weather variables, as judged by the UK Index impact metric in a data denial experiment, was the surface network of land and marine observations, which delivered particular benefit to visibility, 2-metre temperature and 10-metre wind forecasts.

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1 Introduction

High-resolution numerical weather prediction (NWP) models are intended to produce more detailed forecasts than those available from global models. This additional detail is made possible by a finer computational grid which permits a more detailed prescription of terrain and coastlines and more explicit treatment of physical processes.

Like global models, high-resolution models are initialised through the assimilation of observations. However, the observation requirements in a high-resolution system are driven by the desire to resolve phenomena on finer spatial and temporal scales than those that can be adequately represented in a global system, for example thunderstorms, squall fronts and fog. Hence, those observing systems which report frequently and at high resolution tend to be relatively more important for prescribing initial conditions in high-resolution modelling than for global modelling. Proper initialisation of physical processes requires detailed observations of the standard variables of temperature, moisture, and wind but also of variables that have a direct bearing on convective-scale processes at the surface and in the atmosphere. For initialising diabatic processes, the presence or absence of clouds and precipitation, and information on hydrometeors are important.

Because high-resolution forecasts are updated rapidly, the timely collection and processing of observations is important, usually within one hour or less. High-resolution assimilation cycles are generally less than six hours, with hourly cycling becoming increasingly common.

The benefits from rapidly repeated initialisations are naturally greatest during the early stages of a forecast. However, because most high-resolution models depend upon global models for their lateral boundary conditions, the duration of marginal benefit from high-resolution forecasts is effectively limited by the size of the model domain.

2 Impact of continuous high-resolution data assimilation

2.1 Previous Work

A recent study to measure the benefit of data assimilation in the operational North Atlantic & European (NAE) model (Jones and Macpherson, 2012) found that continuous NAE assimilation gave significantly better screen temperature and visibility verification over the UK during the first 24 hours of the forecast. However, for other fields, the run starting from an interpolated global analysis generally performed better. Furthermore, initial conditions interpolated from the 25km global model gave better results than those from the previous 40km global model. These results highlight the benefit of increasing analysis resolution in both downscaled and continuous assimilation configurations. In the latter case, the benefit is likely to arise from observations which are related to the enhanced orographic detail in a high-resolution model, such as screen temperature.

Extrapolating expectations from the NAE study to the current study in the 4km (UK4) model, one might anticipate greater benefits from continuous DA relative to the downscaled global analysis due to the greater differential in resolution ie we are

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comparing a downscaled 25km global analysis in both studies on the one hand, to 12km (NAE) or 4km (UK4) continuous DA systems on the other. Countering this somewhat, the smaller size of the UK4 model domain will generally reduce the longevity of any benefits that may accrue relative to those in the NAE, where they typically persist for up to 24 hours.

2.1.1 Marginal benefit of the continuous UK high-resolution DA system

It is of interest to estimate the marginal benefit of data assimilation in a high-resolution NWP system relative to the cheaper alternative of starting from an interpolated coarser scale analysis of the driving model, in our case a global model. The UK high-resolution DA system, whose key characteristics are listed in Appendix 1, ought to benefit from finer resolution, for example in analysis of features related to orographic detail. In principle, one should also be able to assimilate observations with a lower value for the error of representativity, although this may be difficult to estimate in practice. We also expect benefit to be gained from additional observation types that are assimilated in the high-resolution, but not the global, DA system.

However there are several reasons why a high-resolution assimilation system could potentially be disadvantaged when compared with the global assimilation system. These are:

- the global analysis inside the high-resolution domain may be improved by observations outside the domain, which are not available to the high-resolution analysis.
- high-resolution analysis boundary conditions enforce zero increments for scalar variables at the boundary, meaning that observations close to the boundary are not optimally used.
- finally the global analysis at the Met Office employs 4DVAR whereas the UK high-resolution assimilation uses the cheaper 3DVAR algorithm. In particular, we might expect more effective exploitation of asynoptic observations with 4DVAR.

In addition to the more fundamental issues listed above, there are some practical aspects, related to operational scheduling constraints, which also have the potential to handicap the high-resolution system relative to the global:

- the high-resolution analysis is run with a shorter data cut-off (75 minutes) than the global (120 minutes) and so misses later observations.
- mismatches between applied lateral boundary conditions (lbcs) and background states. For example, the operational 03 UTC UK4 run uses the latest available lbcs (from the global 00 UTC forecast) but receives its T+3 background from the preceding 00 UTC UK4 cycle, which itself was driven by the 18 UTC global forecast. Hence the background (generated from 18 UTC global lbcs) is inconsistent with the applied 00 UTC global lbcs on the 03 UTC cycle, resulting in a discontinuity at the boundaries which then propagates into the domain as the 03 UTC forecast progresses. This situation has the potential to degrade the early part of the forecast and is repeated on the 09, 15 & 21 UTC cycles. Work is ongoing at the Met Office to assess various techniques which may alleviate this effect (Inverarity, *personal communication*).
- a more general comment in relation to boundary conditions may also be made. In general, the realisation of marginal benefit from high-resolution data assimilation will be reliant on the supply of reasonably accurate lbcs containing large-scale dynamical information. It would be unrealistic to expect high-resolution data

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assimilation to be effective if the large-scale forcings are not adequately represented in the model background fields. Colle *et al.* (2000) showed that there was a significant increase in short-range precipitation skill when poor large-scale forecasts, defined by wind speed and direction errors at 850mb, were excluded from the verification.

The above issues notwithstanding, we would in general expect the advantages of high-resolution data assimilation to outweigh the disadvantages by some margin; otherwise it would not be possible to justify the additional resources required by an operational high-resolution DA system. However it is useful to confirm and characterise the nature of this advantage in practice eg which variables benefit most from high-resolution DA, how consistently and in which meteorological situations. Another consideration is the persistence of benefit into the forecast and whether DA can deliver sufficient advantage at very short lead times for the high-resolution NWP model to be used as the primary nowcasting tool in place of extrapolation techniques.

2.1.2 High-resolution observation network design considerations

This part of the study seeks to demonstrate the relative value of the different observing systems currently comprising the UK DA system for high-resolution NWP. To accomplish this we perform Observing System Experiments (OSEs) to measure the impact when we deny the various individual constituent observing systems, as well as some key subcomponents, that comprise the UK observation network. By doing so, we hope to provide guidance on future resource allocation decisions related to the high-resolution observing system. Similar experiments are coordinated by EUCOS to help in the definition of European observation network requirements (Klink *et al.*, 2009).

We should bear in mind that the impact of any single data type depends on the mix of other data types assimilated in any particular NWP system (Andersson and Sato, 2012). Furthermore, the assimilation algorithm employed in a DA system may be preferential to certain classes of observations. Hence substantial differences can be found between results reported by different high-resolution NWP centres (Andersson and Sato, 2012). Indeed, results from global observation impact studies tend to exhibit more homogeneity between centres than those from high-resolution experiments (Andersson and Sato, 2012), most likely because the observation mix in global systems tends to be more standardised, and observation totals are larger (better sampling). We should therefore consider the results from the OSEs presented here as only directly pertinent to the contemporary Met Office high-resolution DA system.

3 Experiments

3.1 Outline

Our main aim in this study is to measure the added-value delivered by the operational continuous UK high-resolution DA system benchmarked against forecasts starting from an alternative candidate analysis. For the purposes of this study we will use a configuration based on the UK4 downscaler (UK4X), operational between November 2010 and summer 2013, as the standard relative to which we will derive the added-value from the high-resolution DA system.

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A further question that we would like to address is how much of the total benefit from the high-resolution DA system originates in the greater resolution of the high-resolution model and how much is due to those additional observation types which are exclusively used in the high-resolution observing system. In order to ascertain this, we define the total benefit from the high-resolution DA system as equal to the sum of that due to resolution effects, plus that arising from the additional observations only used in the high-resolution system ie

Total Benefit of high-resolution DA	=	Benefit from higher-resolution analysis	+	Benefit from observations only used in the high-resolution DA system
A	=	B	+	C

We therefore have performed an additional trial where we deny the high-resolution specific observation types from the continuous high-resolution DA system in order to estimate C, and thus derive B from A - C.

It is pertinent to note that the UK4X does not employ prognostic aerosol, instead using a forecast murk aerosol field which is set to a fixed value.

In order to make a clean comparison between our UK4 experiments and the UK4X, we synchronised the use of global lateral boundary conditions in the two models, so that at the verified forecast run times of 00 UTC, 06 UTC, 12 UTC and 18 UTC, both the UK4 and UK4X are using the latest (hh-0) global lbcs. This is contrary to operational practice in the UK4 (and UKV) which use older (hh-6) lbcs at these data times due to scheduling considerations.

3.2 Trial configurations for marginal benefit trials

The three UK4 trial configurations trialled were as follows:

- CONTROL (the operational OS29 UK4 with continuous high-resolution DA)
- UKDS (starting from a downscaled 25km global model analysis with no high-resolution DA performed)
- UKNHR (as the Control, but omitting those observation types that are exclusively used in the high-resolution DA system).

Forecasts to T+24 are run from the 00 UTC, 06 UTC, 12 UTC, & 18 UTC cycles to eliminate the effect of the normal 3-hour operational stagger and facilitate precipitation verification.

The main experiment (UKDS) measures the benefit of the full operational UK4 DA system relative to the UK4 downscaler. The second experiment (UKNHR) measures the fraction of that benefit which may be attributed to the assimilation of extra observations not used by the global assimilation (by omission of these observations from the high-resolution assimilation). The difference between UKNHR and UKDS represents the benefit derived solely from performing the data assimilation at convective-scale rather

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than global model resolution ie it excludes the impact of any additional high-resolution observation types, as outlined in section 3.1 and Table 1.

'High-resolution' Observation Types assimilated in the UK4 & UKV models but not in the Global model	**'Conventional' Observation Types assimilated in both UK and Global models**
• MOPS Cloud Fraction Analysis • Radar Rainrate (for Latent Heat Nudging) • Doppler Radial Winds • OpenRoad Roadside T2m & RH2m (Highways Agency sites) • Visibility	• Surface (LNDSYN, SHPSYN, BUOY, BOGUS, MOBSYN, METARS) • Aircraft (AIREPS, AMDARS, BOGUS, TCBOGUS) • Sonde (TEMP, PILOT, DROPSOND, WINPRO) • Scatwind (ESAUWI, ASCATHR) • Satwind (MSGWINDS) • GNSS (GPSIWV) • SEVIRIClear (MSGRADUK)

Table 1: Classification of different assimilated observation types according to exclusivity or otherwise to the high-resolution UK models

3.3 Trial periods

Three 5 to 6 week long trial periods were chosen essentially at random from a weather perspective (other than a desire to sample different seasons). A fourth period was added (March 2012) as it included an episode when the UK4 and UKV models both performed notably poorly with regards to their cloud, and consequently temperature, forecasts under a Sc regime, in contrast to the UK4X downscaler.

Period	**Dates**	**Days**
July 2011	01/07/11 to 10/08/11	40
November 2011	01/11/11 to 14/12/11	45
January 2012	03/01/12 to 10/02/12	38
March 2012	10/03/12 to 31/03/12	21

Table 2: Trial periods for marginal benefit trials

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4 Results

4.1 Marginal benefit trials

4.1.1 UK NWP Index

The overall benefit of running the UK models has been assessed for several years by the UK NWP Index, whose components measure the skill of forecasts for screen-level temperature, 10-metre wind, screen-level visibility, 6-hourly precipitation accumulation, total cloud amount and cloud base height using observations at UK land stations. For the purposes of this study, we also include observations from the Republic of Ireland to enhance the sample size.

Period	Days	UK Index Benefit from full high-resolution DA system	UK Index Benefit from high-resolution obs types	UK Index Benefit derived from doing high- rather than global-resolution DA
July 2011	40	+2.54%	-0.96%	(2.54 - -0.96) = +3.50%
November 2011	45	+1.17%	+0.28%	(1.17-0.28) = +0.89%
January 2012	38	+0.78%	-0.18%	(0.78 - -0.18) = +0.96%
March 2012	21	-4.83%	-4.47%	(-4.83 - -4.47) = -0.36%

Table 3A: Overall UK Index Benefit to T+36, relative to downscaler

Table 3A appears to vindicate data assimilation at high-resolution, given the consistent benefits shown over three substantial periods as measured by a basket of indicators, forming the UK Index. The Index benefit appears to be strongest during the summer period. However, more extensive trialling would be required to confirm that this is truly a seasonal phenomenon. Furthermore, the element that contributes most to this positive index score is visibility (see Table 3B), thus this signal might not be significant given the reduced occurrence of low visibility conditions during the summer months. It should be noted that the overall picture presented here is somewhat skewed by the 5-day March Sc event, during which conditions proved to be unusually sensitive to high-resolution DA - this period is considered in more detail later.

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4.1.2 Surface Variables

* Variables 'anticipated' to benefit most from assimilation of high-resolution specific observation types
® Variables 'anticipated' to benefit most from enhanced analysis resolution

Trial	Period	*Vis	*Precip	*Cloud Cover	*Cloud Base Height	®Temp	®Wind	Overall
UK Index Benefit of full high-resolution DA system	Jul 2011	+0.268	+0.151	+0.019	+0.010	+0.078	+0.006	+2.54%
	Nov 2011	+0.083	+0.123	+0.017	+0.063	+0.019	-0.011	+1.17%
	Jan 2012	+0.073	+0.077	-0.034	+0.080	+0.026	-0.024	+0.78%
	Mar 2012	-0.321	-0.095	+0.008	-0.086	-0.349	-0.197	-4.83%
UK Index Benefit from high-resolution observation types	Jul 2011	+0.036	+0.078	-0.046	-0.000	-0.252	-0.018	-0.96%
	Nov 2011	-0.011	+0.051	+0.033	+0.016	+0.002	-0.023	+0.28%
	Jan 2012	+0.056	-0.064	+0.029	+0.017	-0.066	-0.017	-0.18%
	Mar 2012	-0.333	+0.007	+0.082	-0.101	-0.525	-0.091	-4.47%
UK Index Benefit derived from doing convective- rather than global-scale data assimilation	Jul 2011	+0.232	+0.073	+0.065	+0.010	+0.330	+0.024	+3.50%
	Nov 2011	+0.094	+0.072	-0.016	+0.047	+0.017	+0.012	+0.89%
	Jan 2012	+0.017	+0.141	-0.063	+0.063	+0.092	-0.007	+0.96%
	Mar 2012	+0.012	-0.102	-0.074	+0.015	+0.176	-0.106	-0.36%

Table 3B: UK Index Benefit by Component

Table 3B breaks down the headline UK Index results shown in Table 3A into the constituent index components, the overall figure being an average over the 5 variables (the two cloud components are weighted by 0.5 relative to the other variables).

- ®T_{2m}

Overall there appears to be benefits for T_{2m} verification from high-resolution data assimilation. This is most consistently realised by assimilating at the greater resolution of the high-resolution model, while the net effect of additional high-resolution observation types may reduce this benefit. There is evidence that this detrimental impact of extra data mainly comes from assimilating the MOPS cloud analysis, which can lead to errors in cloud cover with a consequential impact on the T_{2m} scores.

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- ®$Wind_{10m}$

For 10-metre wind there is a slight rms degradation in DA trials relative to downscaler up to about T+6 in three of the trial periods, with results similar thereafter. In the fourth (March) period the degradation is somewhat greater, especially in the full high-resolution DA trial, and extends to T+24, whilst also accompanied by a more noticeable (less negative) difference in bias.

Although the differences are minor, it is somewhat disappointing that 10-metre wind verification in the DA trials fails to capitalise on the additional orographic detail in the UK4 model compared to the global. This may be partly due to difficulties in assimilating near-surface wind observations as discussed by Ingleby (2013).

- *Visibility

Log_{10} visibility appears to be generally superior in the full high-resolution DA system, although this measure is largely sampling the relatively uninteresting clear end of the visibility spectrum. This certainly would be expected as the downscaler lacks both a prognostic aerosol murk field and also the assimilation of visibility observations. The advantage over the no high-resolution observations configuration is less than that over the downscaler (greatest in the November and January periods), presumably because this configuration does still have a prognostic aerosol field (including murk emission sources) although no assimilation of visibility observations.

In terms of Equitable Threat Score (ETS), the skill scores for the 4000m threshold broadly reflect those for log_{10} visibility. However, the picture is much more mixed at the foggy (200m) threshold, where, if anything, the no high-resolution observations configuration does better, although the caveat should be added that the sample size for this category (ie fog occurrences) was generally low for all four periods. Also, in addition to aerosol, surface relative humidity bias plays an important role at this threshold, and this can be influenced eg by cloud assimilation, either via the moisture covariances or a surface temperature effect as a result of a bias in cloud cover. Indeed, the latter appears to be responsible for the poor visibility performance of the full high-resolution DA system relative to the MOPS cloud denial experiment for the March period, as shown in section 4.3.2.

- *Precipitation

Period / Intensity	Light	Moderate	Heavy
July	DA, DS, NHR	DA, NHR, DS	DA, DS, NHR
November	DA, NHR, DS	DA, NHR, DS	NHR, DA, DS
January	NHR/DA, DS	NHR, DA, DS	NHR, DS, DA
March	DS, DA/NHR	DS, NHR, DA	DS/NHR/DA

Table 4: Order of ETS precipitation performance by period and threshold

For 6-hourly precipitation accumulation, the full high-resolution DA model is the best performer across the intensity spectrum during the July period, whilst also doing better for light and moderate precipitation during November. The trial without the high-resolution observation scores best during January, while the downscaler comes out on top for the March period (noting that March was a relatively dry month). A common

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feature of the T+6 accumulation across most intensity-period combinations was for the downscaler frequency bias to be the lowest, and the trial without additional high-resolution observations tended to have the highest frequency bias. The full high-resolution DA system tends to come somewhere between these two. This highlights a known weakness in the downscaler – it is too slow in spinning-up precipitation, particularly in showery airstreams.

The reason for the increase in the precipitation frequency bias at T+6 when denying the high-resolution specific observation types is considered more closely in 4.3 (single variable denials). It also hints that, at least on average, the role of radar-rain rate assimilation (one of the 'high-resolution specific' observations) by latent heat nudging (LHN) is to reduce rather than increase precipitation rates.

- *Cloud Cover

For rms fractional total cloud cover (verified against automatic observations only), the downscaler is the best performer, except in the March period when the full high-resolution DA system is better up to about T+6. Categorical ETS scores, on the other hand, paint a rather different picture with the full high-resolution DA system, including assimilation of MOPS cloud cover, consistently doing better during the early forecast stages (typically up to about T+6) across all three cloud thresholds. This rather suggests that the downscaler is predicting overall cloud amounts better, whereas MOPS cloud cover assimilation improves the placement of cloud, at least for the first few hours.

- *Cloud Base Height

For cloud base height (against automatic observations only), we see the full high-resolution DA system performing better than the downscaler over two of the trial periods (November and January), with little difference for the July period, and the downscaler doing best during the March period. There appears to be a fairly general tendency for the downscaler to forecast lower cloud base heights compared to the trials with data assimilation. Of possible relevance to the problematical March Sc period is the under-forecasting and detection of cloud bases less than 100m, more particularly at times beyond T+6, in the full high-resolution DA system trial.

- ®RH_{2m}

There appears to be a fairly consistent signal for a dry bias in RH_{2m} from the full DA system which is less evident in the downscaler, or where the extra high-resolution observations are denied. This could be a result of a warm T_{2m} bias which might be caused by cloud biases associated with the MOPS cloud assimilation. It may also be associated with the vertical spreading of humidity increments by the humidity covariances.

Though RH_{2m} is not a UK Index component, any bias will have consequences for visibility verification, particularly in the colder fog-prone seasons, and possibly also for cloud base height.

- MSLP

For mean sea-level pressure (not part of the UK NWP Index), the downscaled model verifies better than the full high-resolution DA model over two periods (November and March), about the same in January, and worse in July in terms of rms error. There is rather more consistency with respect to bias, the downscaler generally having a less positive bias relative to the full high-resolution DA configuration. The impact of the additional high-resolution observation types is generally mixed and small for MSLP.

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4.1.3 Upper-air fields

Although the primary purpose of running a high-resolution DA system is to improve prediction of surface weather elements, it is worth comparing the UK4's upper-air performance with the downscaled model.

For temperature, RH and wind, the downscaler has smaller rms differences at T+0 than the configurations with DA. This is no doubt due to the fact that in limited-area 3DVAR, use of the Incremental Analysis Update (IAU) means that only half the analysis increment has been added by T+0, while the downscaler starts from an interpolated global analysis made via 4DVAR, in which the full analysis increment has been added several hours earlier. The downscaler does verify slightly better at T+6, and in some instances its advantage can still be seen at T+12. Trials with data assimilation seem to have less of a warm bias up to about 400 hPa relative to the downscaler in three of the four periods. Also, relative to the no high-resolution observations trial, the full high-resolution DA trial appears to be moistening the lower levels, say up to around 700 to 600 hPa, whilst drying the profiles further up. This behaviour probably comes from the assimilation of MOPS cloud data.

4.1.4 Case Studies

- March 2012 Stratocumulus

The period 10th -15th March 2012 was characterised by poor operational cloud forecasts under a blocked Sc regime, which provided the motivation for examining the role of high-resolution DA in this situation. Operational T_{2m} verification was particularly hit by the failure to accurately pinpoint breaks in the Sc sheet during this period. Figure 1 shows that the trial with full high-resolution DA (ie the operational configuration) fails to capture the extent of the cloud breaks down the eastern side of England at both T+7 and T+1 whilst also erroneously inserting breaks over northeast Scotland at T+1. The DA trial omitting the high-resolution DA observation types more accurately depicts the eastern England cloud breaks, although also mistakenly has breaks over the northeast at T+1. The UK4 downscaler actually has the best grasp on the cloud cover, with breaks over Eastern England (though still not quite as extensive as the satellite image), whilst keeping northeast Scotland cloudy. This appears to be an example where high-resolution DA is responsible for an inferior short range forecast than could otherwise be obtained by starting from a downscaled global analysis.

A further trial was run which denied just MOPS cloud (rather than all of the additional high-resolution observation types). Figure 2 indicates that the 'no MOPS cloud' trial behaved similarly to both the downscaler and the no high-resolution DA observation trials in terms of cloud cover bias, whereas the full DA configuration clearly has too much cloud cover. We conclude that the excessive cloud amounts in the full DA forecast over this period may reasonably be attributed to the assimilation of MOPS cloud.

Another interesting characteristic of the cloud bias behaviour in the full DA trial (Figure 2), is that it starts from close to neutral at T+0 before rising to a plateau between T+9 and T+15, before falling away again during the latter stages of the forecast. This appears to be consistent with the assessment that the model boundary layer was too deep and moist and, as a result, low cloud became too persistent. Similarly the warm temperature bias (and RMS) is a minimum at T+0 and peaks round about T+18.

The poor cloud performance encountered over this period was instrumental in the operational move from MOPS cloud assimilation to GeoCloud satellite observations in

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combination with surface cloud reports. The performance of this alternative approach to cloud assimilation over the March 2012 period is briefly discussed in section 4.4.1.

- November 2011 Low Cloud

On this occasion the full DA configuration succeeds in outperforming the downscaler and no high-resolution observation trials by more accurately capturing the extent of the principal cloud break over south-eastern England in anticyclonic conditions not too dissimilar to the previous March case.

- December 2011 Showery Convection

In this example Figure 3 shows that the downscaler is obviously deficient in showers at T+1, whereas both DA trials (full and no high-resolution observations) give a much more convincing portrayal, although the precipitation in the full DA configuration is arguably too organised, whilst both miss showers over southwest Ireland. This spin-up behaviour in the downscaler is a consequence of reconfiguring a global scale analysis with moisture structures determined by parameterised convection to a smaller convection permitting scale. Therefore, the advantage conferred by the two DA configurations is due to a better resolution of the convection processes, rather than assimilation of observations. By T+3 the downscaler is showing signs of developing its own showers.

4.1.5 Short-period UK NWP Index

In general, we expect the impact from DA to be weighted towards the earlier forecast lead times, with the encroachment of information from lateral boundary conditions reducing differences from the downscaler at longer forecast ranges. With this in mind, the UK Index calculation was truncated at T+12, rather than the usual T+36. Table 5 appears to confirm this expectation, with the DA impact as measured up to T+12 being approximately double that indicated by the 'standard' UK Index calculation to T+36 over the November 2011 period.

Period	Days	UK Index	UK Index Benefit from full high-resolution DA system	UK Index Benefit from high-resolution obs types	UK Index Benefit derived from doing high- rather than global-resolution data assimilation
November 2011	45	T+36	+1.17%	+0.28%	(1.17-0.28) = +0.89%
November 2011	45	T+12	+2.22%	+0.59%	(2.22-0.59) = +1.63%

Table 5: Short-period UK NWP Index to T+12 compared to Standard T+36 Index

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4.2 Additional trials in the UKV

In order to test whether observation impacts in the UK4 model could be considered indicative of performance in the higher resolution (1.5km) UKV model, a UKV experiment was run over a single period using observation configuration analogous to the UK4 experiment ie a full operational UKV DA system was compared to a UKV system starting from a downscaled global analysis, with an additional high-resolution observation type denial to gauge the relative impacts from resolution and high-resolution specific observation types.

The analysis grid resolution used in the UKV is half that of the model, ie 3km rather than 1.5km. It should be noted that the UKV DA high-resolution system tested here was a later configuration (UM OS31, DA PS32) than the UK4 configuration (UM & DA PS29) used in this study, hence cross-referencing the results between the two model requires a degree of caution. In particular, cloud assimilation moved from MOPS cloud at PS29 to GeoCloud plus Surface cloud at PS32.

An additional UKV experiment (UKVNODA) was also performed in order to estimate the benefit arising from the downscaled global analysis. This was started on the first cycle from an interpolated global analysis, but with no further update of the interior analysis, so that the sole forcing was through the 6-hourly updates of the global lateral boundary conditions.

4.2.1 Marginal benefit of assimilation in the UKV relative to the UK4

Table 6A compares the marginal benefits in the UKV, as deduced from trials run over the November 2011 period, to corresponding values found earlier in the UK4.

There appears to be broad agreement between the pattern of marginal benefits yielded by the UK4 and UKV compared to their respective downscalers, although some differences in detail. The major discrepancy between the two models is visibility, with the UKV appearing to deliver substantially more benefit from high-resolution data assimilation than the UK4, thanks mainly to assimilating at a higher resolution. It is likely, though not actually proven, that a large part of this difference lies in the introduction of the UM stable boundary layer package at PS31 in the UKV (the UK4 was frozen at PS29), which was responsible for a visibility detriment due to a shift in RH bias. The discord for visibility is largely responsible for the disparities in the overall UK Index, although there are also less significant differences for other variables.

Whilst a large degree of caution is required, due to the use of a later (PS32) assimilation configuration in the UKV and the single period involved, there is some suggestion that the benefit gained from the full high-resolution data assimilation system is greater in the UKV than in the UK4.

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November 2011								
Trial	**Model**	**Vis**	**Precip**	**Cloud Cover**	**Cloud Base Height**	**Temp**	**Wind**	**Overall**
UK Index Benefit of full high-resolution DA system	**UK4**	+0.083	+0.123	+0.017	+0.063	+0.019	-0.011	**+1.17%**
	UKV	+1.270	+0.193	-0.001	+0.090	+0.038	-0.013	**+4.26%**
UK Index Benefit from high-resolution obs types	**UK4**	-0.011	+0.051	+0.033	+0.016	+0.002	-0.023	**+0.28%**
	UKV	-0.187	+0.022	+0.038	+0.021	+0.032	-0.012	**-0.23%**
UK Index Benefit derived from doing high- rather than global-resolution data assimilation	**UK4**	+0.094	+0.072	-0.016	+0.047	+0.017	+0.012	**+0.89%**
	UKV	+1.399	+0.177	-0.038	+0.068	+0.010	+0.003	**+4.56%**

Table 6A: Comparison of marginal benefits over their respective downscalers in the UK4 and UKV models for the November trial period

4.2.2 Relative benefit of downscaled and continuous DA

In this section we attempt to compare the benefits accruing from downscaled (DS) and continuous high-resolution data assimilation (DA) relative to a baseline configuration where the only forcing is through the lateral boundaries (no DA). The relevant trial results are presented in Table 6B, where the final row summarises the ratio of downscaler benefit to high-resolution data assimilation benefit.

Taken overall in UK Index terms, the benefit of downscaling the global analysis (relative to no interior DA), is approximately one fifth of that gained from continuous high resolution DA. However, this headline number is of little use, as it masks very variable contributions from Index components. At one end of the spectrum we see that high-resolution data assimilation conveys considerable benefit for visibility, whereas the downscaler actually results in a slight detriment. This is most likely a consequence of the inclusion of prognostic murk plus emission sources in the UKVNODA trial, features which were both lacking in the downscaler configuration. In other words, had the downscaler not been handicapped by the omission of prognostic murk aerosol, we could realistically expect an improved visibility impact from the downscaler relative to the UKVNODA trial, and hence a reduction in the disadvantage relative to continuous DA.

At the other end, we see that, whilst both assimilation systems give a positive impact for wind, the downscaler contribution exceeds that from high-resolution DA by 20%. Other variables that benefit more from high-resolution DA are, in increasing order,

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cloud base height, temperature, and precipitation. Cloud cover sees roughly equal benefits from a downscaled analysis and high-resolution DA.

November 2011								
Trial	**Model**	**Vis**	**Precip**	**Cloud Cover**	**Cloud Base Height**	**Temp**	**Wind**	**Overall**
UK Index Benefit	**UKV DA (vs DS)**	+1.270	+0.193	-0.001	+0.090	+0.038	-0.013	**+4.26%**
	UKV DA (vs No DA)	+1.168	+0.269	+0.098	+0.160	+0.210	+0.060	**+5.31%**
	UKV DS (vs No DA)	-0.101	+0.076	+0.099	+0.067	+0.169	+0.072	**+1.08%**
	DS Benefit / DA Benefit	-9%	28%	101%	42%	80%	120%	**20%**

Table 6B: Relative UK Index benefit of downscaled global analysis and continuous DA for the November trial period

Finally, to add some perspective, Mittermaier (*personal communication*) has calculated that over the last 3 years, the full UKV system gave an added value of approximately 10% in UK Index terms relative to the global analysis and forecast system. (In the calculation of this estimate, UKV forecasts at T+9,15,21,27,33 are compared with global forecasts at T+6,12,18,24,30. For the same verifying time, therefore, the UKV forecasts are driven by a 6-hour older global run, thus disadvantaging the UKV. Hence the added value estimate must be an underestimate of the quality of the underlying UK forecast system). If we assume that the figure in Table 6B of 4.26% for DA benefit (vs DS) found in the November 2011 experiment is representative of the longer term average, then we might roughly attribute about 40% of the benefit arising from the UKV model (relative to the global model) as coming from high-resolution data assimilation. Again though, as noted above, this estimate of DA benefit is inflated by the omission of prognostic murk from the downscaler. If, more realistically, we assume that prognostic murk is mainly responsible for the improvement in ETS for the 4km visibility threshold after T+12, then the fraction of total benefit owing to high-resolution assimilation is estimated at 27%. This applies to the whole 36-hour forecast period. Based on the factor of two revealed in Table 5, one might surmise that over the first 12 hours, the proportion might be around one half.

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November 2011								
Trial	**Model**	**Vis**	**Precip**	**Cloud Cover**	**Cloud Base Height**	**Temp**	**Wind**	**Overall**
UK Index Benefit	**UKV DA (vs DS)**	+1.867	+0.632	+0.069	+0.261	+0.141	-0.030	**+5.62%**
	UKV DA (vs No DA)	+1.747	+0.890	+0.320	+0.449	+0.562	+0.181	**+7.93%**
	UKV DS (vs No DA)	-0.111	+0.259	+0.253	+0.187	+0.415	+0.210	**+2.46%**
	DS Benefit / DA Benefit	-6%	29%	79%	42%	74%	116%	**31%**

Table 6C: Relative short-period UK Index benefit to T+12 of downscaled global analysis and continuous DA for the November trial period

Table 6C presents the results shown in Table 6B in short-period index format ie truncated at T+12. This gives an indication of the relative contributions over what may be considered as the nowcasting period. In general the benefits from both high-resolution DA and the downscaled analysis are larger at these shorter timeframes, which is not surprising. The exception to this is the visibility component in the downscaler, where the impact relative to the no DA trial is very similar in both the abbreviated T+12 index and the full T+36 index. This suggests that the visibility impact is spread evenly over the forecast ranges up to T+36, rather than weighted towards the earlier period as we might expect from a more typical DA impact. This is probably a consequence of the lack of prognostic murk and emissions in the downscaler. The downscaler to local DA benefit ratios for the other variables are similar in the T+12 and T+36 indices, with the exception of cloud cover, which appears to benefit relatively more from local DA in the early part of the forecast.

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4.3 Observation System Denials

The five additional UK4 configurations trialled for this part of the study were as follows:

- NO SAT : CONTROL minus satellite observations (SATWIND, SCATWIND, SEVIRI Clear Sky Radiances)
- NO SURF : CONTROL minus 2-metre and 10-metre surface (land and marine) observations
- NO UAIR : CONTROL minus sonde and wind-profiler observations
- NO ACRF : CONTROL minus aircraft observations
- NO RAD : CONTROL minus radar rain-rate and Doppler radar observations

The observation network denial trials were run over a single (November 2011) period.

4.3.1 Observation Network Denials

November 2011							
	Vis	Precip	Cloud Cover	Cloud Base Height	Temp	Wind	Overall
Surface	+0.111	+0.253	+0.027	+0.022	+0.195	+0.118	+2.90%
Satellite	-0.014	+0.235	+0.025	+0.021	+0.056	+0.101	+1.69%
Upper Air (excluding aircraft)	+0.038	+0.276	+0.025	+0.032	+0.053	+0.102	+2.10%
Aircraft	+0.055	+0.253	+0.027	+0.017	+0.052	+0.095	+1.99%
Radar	-0.006	+0.237	+0.022	+0.018	+0.048	+0.091	+1.64%
High-resolution (all obs networks not in global model)	-0.011	+0.051	+0.033	+0.016	+0.002	-0.023	+0.28%

Table 7: UK Index Benefit of different observation networks implied by denial trials

Table 7 indicates the benefit contributed over a single trial period, November 2011, by the various UK observation networks that make up the UK observation system as implied by the impact on the UK Index metric (and its constituents) arising from their denial.

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It is gratifying to see that, with the possible exception of the high-resolution specific observation category, there are tangible benefits in verification arising from each of the individual observing networks in the UK observation system. We should bear in mind, however, that the impact of the whole high-resolution DA system is likely to be less than the sum of the individual network impacts, especially in a relatively data-dense region. A degree of redundancy would be expected, so that remaining observations have the capacity to compensate to some extent for those that are withdrawn (Gelaro and Zhu, 2009).

The network of surface land and marine observations appears to deliver the greatest index impact, notably for visibility, precipitation, surface temperature and surface wind. In addition, surface observations also play a large role in constraining MSLP. Withdrawing the surface observations results in a systematic gain in MSLP bias, which is similar, although opposite in sign, to that seen in global denial trials (Dumelow, 2005).

The second largest provider of UK Index benefit is the upper-air network of radiosondes and wind profilers. Indeed the overall impact from this network is probably understated by the UK Index impact, given that this observation network clearly has the greatest influence in improving upper air temperature, relative humidity and wind profiles, which is an aspect not included in the UK Index.

All the major networks (barring the high-resolution specific category) appear to make measurable, and similar in magnitude, contributions to the accuracy of precipitation predictions. This is broadly in line with the findings of Anderson *et al.* (2002), although that study used a rather different 'case-study' methodology and did not explicitly consider satellite data impacts (other than MOPS cloud). On the other hand, none of the networks really yield any significant benefit for cloud cover and cloud base height verification, which, taken at face value, is rather disappointing and indicates a weakness in the high-resolution DA system. However, this may also reflect the greater uncertainty which accompanies observations of cloud and can potentially lead to less reliable verification (Mittermaier, 2012).

Although the observations included under the high-resolution specific umbrella appear to underperform relative to the other networks, the constituent observation types included in this category are quite disparate in nature and therefore we seek to understand this disappointingly small overall signal by interpreting additional single observation type denial experiments as described in the next section. It should be noted, though, that these extra experiments were performed on different periods from the November 2011 one used in table 7, so our inferences are indirect.

4.3.2 Single Observation Type Denials

- Radar rain-rate

A single variable denial experiment for radar rain-rate during July 2011 points towards a modest benefit in precipitation verification through the assimilation of radar rain-rates by Latent Heat Nudging (LHN). Whilst there is little change in the frequency bias for the main UK Index 6-hourly accumulation thresholds (0.5mm, 1mm & 4mm) without the radar rain-rate observations, the change in both the probabilities of detection and false detection are unfavourable, suggesting that LHN benefit is achieved primarily through better placement of the precipitation. For the 0.5mm and 4mm thresholds, there is slight evidence of 6-hourly accumulation benefit up to T+24. Similarly, for hourly accumulation thresholds of 0.2, 0.5, and 1.0 mm/hr there appears to be statistically significant benefit

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up to at least T+6, with further though decreasing advantage beyond this up to about T+24. Dixon et al. (2009) found significant benefit from LHN for precipitation forecasts in the UK4 model up to T+3 in convective cases, and some benefit at later times. Tingwell *et al.* (2012) reported LHN benefit up to T+6 in the Australian UM-based 1.5km model, this being attributed to a suppression of incorrect precipitation plus a tendency to spin up weak precipitation.

Trial	Period	Vis	Precip	Cloud Cover	Cloud Base Height	Temp	Wind	Overall
Control minus Radar Rainrate	**Jul 2011**	**-0.050**	**-0.088**	**-0.021**	**+0.007**	**+0.019**	**-0.022**	**-0.74%**

Table 8A: UK Index Impact of denying Radar rain-rate observations

- MOPS Cloud

A MOPS cloud denial experiment over the July 2011 period shares many of the verification characteristics recorded in the high-resolution observation type denial trial reported in section 4.1.1 and appears to account for much of the negative impact, in particular to surface temperature. Although the control with MOPS cloud is better, in rms terms, for surface temperature up to about T+3, there is a reversal in fortunes beyond this point. This appears to coincide with a switch from less cloud to more cloud, relative to the MOPS cloud denial trial, at about the same time.

We also saw in 4.1.2 that removing high-resolution specific observations led to an increase in forecast precipitation frequency bias at T+6. Although it is perhaps intuitive to assign the cause of this increase in forecast precipitation frequency bias to radar rain-rate assimilation by the latent heat nudging mechanism, we saw in 4.3.2 that the withdrawal of radar-rain observations actually has relatively little impact on the T+6 forecast precipitation frequency bias. However, the precipitation frequency bias when we withhold the MOPS cloud observations bears a close resemblance to that when we withdraw all high-resolution specific observations, suggesting that it is the assimilation of MOPS cloud, not radar rain-rate, that is responsible for suppressing the precipitation frequency bias. It is possible that the favourable reduction in the precipitation frequency bias at T+6 with MOPS cloud may be linked to reduced cloud amounts in the early stages as discussed above.

A second MOPS cloud denial experiment for the March 2012 period is discussed in more detail in the case study section (4.1.4). Suffice to say here that this also records a sizeable detriment to surface temperature when MOPS cloud is included.

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Trial	Period	Vis	Precip	Cloud Cover	Cloud Base Height	Temp	Wind	Overall
Control minus MOPS Cloud	Jul 2011	-0.068	-0.023	+0.060	+0.015	+0.245	+0.015	+1.16%
	Mar 2012	+0.669	+0.029	-0.061	+0.112	+0.545	+0.088	+6.43%

Table 8B: UK Index Impact of denying assimilation of MOPS cloud

- GNSS

Some consideration was given as to whether to classify GNSS (formerly known as ground-based GPS, or Zenith Total Delay, observations as a high-resolution specific observation type, but its recent (March 2012) introduction to the global model led to its omission from this category. Nevertheless, we performed single observation denial experiments for this data type over two periods. Both periods recorded positive UK Index impacts from GNSS, with the bulk of the benefit seen in surface temperature. This is consistent with some evidence in a previous study conducted in the Met Office NAE model (Bennitt and Jupp, 2012) of surface temperature bias (though not RMS) impacts from GNSS data, which the authors attribute to improvements in forecast cloud, especially larger fractions, through a moistening of the vertical profile. A similar mechanism appears to be present in our July period, although the profiles are drier (up to about 200 hPa) rather than moister, leading to less cloud and a positive shift in the surface temperature bias, which is accompanied in this case by a reduction in RMS.

Trial	Period	Vis	Precip	Cloud Cover	Cloud Base Height	Temp	Wind	Overall
Control minus GNSS	Jul 2011	-0.065	-0.037	-0.086	-0.034	-0.261	-0.031	-2.45%
	Mar 2012	+0.043	-0.051	-0.004	-0.007	-0.201	+0.002	-1.01%

Table 8C: UK Index Impact of denying GNSS Observations

4.4 Revised cloud assimilation

Endemic problems with stratocumulus representation as typically encountered under stable, blocked conditions like the March 2012 episode described in 4.1.4 were instrumental in prompting a move away from assimilation of the MOPS cloud analysis. The replacement involved separate assimilation of cloud top data derived from SEVIRI (the GeoCloud imagery product introduced in January 2013), in conjunction with surface cloud reports, assimilated operationally from May 2013. For an account of developments in this area, see Renshaw and Francis (2011). This novel combination of satellite and surface data was tested in the UK4 over the March 2012 period, giving rise to substantial UK Index improvements over forecasts using MOPS cloud, especially in surface temperature. However, over the remainder of the extended March period the UK Index is neutral, with a slight detriment for cloud cover compensated by a gain for surface temperature.

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Trial	Period	Vis	Precip	Cloud Cover	Cloud Base Height	Temp	Wind	Overall
Benefit of OS32 cloud DA relative to OS29 cloud DA	March 2012	+0.342	+0.039	-0.014	+0.113	+0.529	+0.106	+5.18%
	Sc period	+0702	+0.007	+0.301	+0.338	+3.723	+0.652	+55.8%
	Post-Sc period	-0.116	+0.037	-0.073	+0.019	+0.114	+0.026	+0.03%

Table 9: Benefit of updated cloud assimilation scheme in the UK4

5 Discussion

Marginal Benefit of High-Resolution Assimilation

The overall results in terms of UK NWP Index show that the marginal benefit from continuous high-resolution data assimilation relative to initialising from a downscaled global analysis is achieved largely by assimilating the same observation types used in the global model, but at the higher resolution. The contribution from extra observations used exclusively in the UK high-resolution model is generally mixed.

Of the high-resolution observation sub-categories, the assimilation of the MOPS cloud analysis has been shown, during certain restricted episodes, to have the potential to cause significant detriment, particularly to screen temperature, whilst also providing some benefit at other times. Partly due to the poor performance during the blocked March 2012 period, the UK cloud assimilation scheme was revised, leading to a significant improvement for the March 2012 period. However, a later blocked period (February 2013) was shown to verify better with the discarded MOPS cloud analysis rather than the recently revised cloud scheme. There is some debate (Lock, *personal communication*) as to whether the cloud errors in the February 2013 period were more a result of the model inappropriately attempting to resolve overturning of the boundary layer, and that the differences in the performance of cloud assimilation schemes simply reflected the extent to which they were able to correct the 'model' error. To sum up, cloud assimilation is clearly a very challenging area and one that is crucial to the consistent derivation of benefit from a high-resolution data assimilation system.

Of the other high-resolution observation sub-categories, radar rain-rate assimilation through latent heat nudging appears to be fairly generally advantageous up to a lead time of 6 hours, with some indication of benefit beyond this. Pre-operational trials of OpenRoad observations from Highways Agency sites conducted over a 2 week winter period in 2011 showed small positive impacts for screen temperature and relative humidity. These signals became rather larger when observations from all OpenRoad sites were assimilated (Figure 4). GNSS data, not categorised here as a 'high-resolution' observation but assimilated in the UK4 since March 2007, have demonstrated positive impact for surface temperature by modifying vertical moisture profiles.

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Overall, the marginal benefit results for a single period in the UKV present a rather similar picture to those found in the UK4, with the exception of visibility and cloud. The discrepancies for these variables might be explained by differences in the DA (& UM) schemes, as the configurations in the UKV trials post-dated those used in the earlier UK4 trials. Although for this reason we are unable to draw firm conclusions on the UK4/UKV comparison, the results do hint that the marginal benefit in the higher resolution UKV model may be greater than in the UK4 model, when compared to their respective downscalers. If this result were confirmed (say by trialling in additional periods), it would suggest that as we move towards even higher resolution models, then we might be justified in anticipating greater returns from high-resolution data assimilation systems.

Influence of synoptic conditions

One factor, inextricably linked to the lateral boundary conditions, is the role of weather type in determining the sensitivity of the overall DA signal, as well as its sub-components. This applies both in high-impact events and over longer characteristic periods. Probably the most significant synoptic distinction is between 'blocked' and 'mobile' conditions. This is because the DA signals, positive or detrimental, under the blocked type are more likely to be amplified, as they persist for longer within the limited area model domain (as demonstrated in the March 2012 Sc episode, section 4.1.4). In the mobile situation, they tend to be 'washed out' more rapidly by the lateral boundary conditions, particularly in smaller domains as discussed above. A further distinction between 'blocked dry' and 'blocked wet' (or 'anticyclonic' and 'cyclonic'), might yield further insight into performance for Sc and rainfall situations respectively. The distinction between blocked and mobile conditions could be achieved subjectively eg by viewing synoptic charts, or by adopting a proxy, for example wind speed, as a more objective, though possibly less precise, method.

Besides this diagnostic aspect, results such as those obtained during the March 2012 Sc episode illustrate the importance of identifying and including similar sensitive periods when trialling modifications to the assimilation system in the high-resolution UK models.

Observation Network Impacts

Of the observation network denials in the UK4, the surface network appears to yield the greatest all-round benefit, followed by the upper air network and aircraft. Assuming that this is a statistically robust result, there are a number of possible explanations why the surface network appears to be the most influential. Firstly, the UK Index metric is weighted towards surface weather elements, hence the large impact from assimilation of surface observations, some of which are used in the UK Index calculations, is perhaps not too surprising. We have also seen that assimilating observations at a higher resolution appears to be beneficial. It seems plausible that a more resolved orography may be responsible for much of this benefit, and therefore those observations most closely linked to orographic detail are likely to provide the greatest additional benefit.

For the convective-scale AROME model, Mahfouf (2012) concluded that surface data, together with GNSS, the Radar network (wind and humidity) and aircraft, were of primary importance. This was based on results using the Degrees of Freedom for Signal (DFS) and reduction of error variance of estimation diagnostics. Whilst there is a fair overlap between the two studies on what is important (surface, GNSS, aircraft) and also what might be rather less important at the high-resolution (eg satellite), it would be unrealistic to expect complete agreement given the different diagnostics and observation usages. The FSO (Forecast Sensitivity to Observations) is an adjoint-based technique for

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calculating the impact of observations, and has yielded useful results in global models (Lorenc and Marriott, 2013). Work is also underway at the Met Office to investigate the feasibility of extending the application of the FSO tool to convective-scale models. Provisional results from this study appear to be rather different from those presented here, in that they point to relatively greater impacts from upper-air observations (Marriott, *personal communication*). However, the measure of forecast error used in the FSO contains a much greater contribution from upper-air fields and so a significant difference might be anticipated.

Cress (2010) also demonstrated positive impacts through the assimilation of screen-level observations on the surface analysis. However he also found neutral to slightly negative impacts from surface observations on the upper-air analysis, most likely due to the excessive vertical spreading of the screen-level information, thus pointing to the need for appropriate vertical structure functions.

Observation Network Design Issues

An important practical consideration for the design or refurbishment of observing systems is the degree of redundancy between the component networks in the system. If, for example, one observing component is reduced or withdrawn on economic grounds, to what extent will the remaining networks be able to compensate for the loss of observing capacity. One question that has received quite a lot of attention recently is whether aircraft observations, particularly ascent/descent profiles near airports, can offset information lost if relatively costly sonde launches are curtailed (Andersson and Sato, 2012). Whilst this is certainly pertinent to high-resolution data assimilation, it is perhaps of more relevance to consider the impact of possible reductions to the UK surface network, which has been shown in this study to deliver most benefit. Indeed, the number of SYNOP sites has declined over the past ten years, although this has been at least partially offset by increases in Climate Data Logger (CDL) sites and the introduction of the OpenRoad observations. It would also be worth establishing whether we could expect additional paybacks from further investments in the surface network. In order to address these questions, we would need to examine in more detail the sensitivity of forecast benefits to components of the surface network, such as SYNOP, CDL, METAR, OpenRoad and drifting buoys.

One particular aspect worth examining is how close we are to surface observation saturation. In other words, would we be justified in anticipating, over what is a relatively data-rich area in global terms, additional positive benefit by boosting the density of surface observations beyond the current value? Or would a reduction in the number of surface observations necessarily prove to be detrimental? Theoretical studies (eg Liu and Rabier, 2002) give some pointers on optimal observation densities (and resolutions) under optimal and sub-optimal data assimilation schemes. Morss *et al.* (2001) contend that, for the same total number of observations, sampling at a greater number of locations is likely to be more beneficial than more frequent sampling at a limited number of locations.

However, real observing systems are comprised of a much more heterogeneous and opportunistic mix of observation types than the rather idealised scenarios considered in these papers, hence the requirement for complementary Observing System Experiments (or similar) to be carried out. The impact from the forthcoming significant expansion in the number and coverage of OpenRoad sites being used in the high-resolution assimilation system should provide some clues as to the scope for further benefits from surface observations. If this were to prove fruitful, then this might be justification for considering other ad-hoc data sources such as the Met Office Weather Observations

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Website (WOW) amateur observation initiative (see http://www.metoffice.gov.uk/wow). Tyndall and Horel (2013) conducted assimilation experiments over the CONUS region that appeared to suggest that the most influential factor in determining the magnitude of an observation impact on the surface analysis was the relative remoteness of the observation location, particularly in volatile weather situations. Observations from the Citizens Weather Observation Program (CWOP) network, analogous in many respects to WOW in the UK, had generally lower than average impacts, due to their tendency to be clustered together in urban areas. Observation impacts from the Road Weather Information System (RWIS), similar to the OpenRoad network in the UK, tended to vary from above average in rural areas to below average in the urban areas. The perceived accuracy of the observing instrument appeared to play only a secondary role in determining the observation impact ie the impact from a less accurate instrument in a poorly observed area is likely to be greater than that from a more accurate instrument in a densely observed area.

Looking to the future, the inexorable trend towards models with even higher horizontal (sub 1km) and vertical (> 100 levels) resolutions, together with more rapid update cycles (hourly or less), will lead to increased observational requirements, both spatially and temporally, plus a need for more timely availability.

Influence of DA Algorithm

The next major development of the assimilation algorithm in the operational high-resolution UK models is expected to be a move from 3DVAR to 4DVAR, perhaps during 2014-15. 4DVAR has been seen to perform better than 3DVAR in a global and regional context (Rawlins *et al.*, 2010), though its extra expense has generally restricted its use in high-resolution applications. 4DVAR was used in the Nowcasting Demonstration Project (NDP) model run for the 2012 Olympics (Golding *et al.*, 2013) whose domain covered the southern UK. 4DVAR can be expected to extract more information from the increasingly abundant asynoptic observations ie those (typically non-manual) observations not occurring at the main synoptic hours. We may therefore tentatively anticipate a relatively greater contribution to the overall impact of high-resolution assimilation from observations that are more frequent. On the other hand, impacts measured in observation denial trials might possibly diminish, as the more efficient exploitation of observations in 4DVAR allows remaining observations a greater capacity to compensate for those observations that have been denied.

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6 Conclusions

- The most consistent benefit of assimilation in the UK models comes from assimilating ‘conventional’ observations at higher resolution than in the global model.

- There is some evidence that the advantage of high-resolution assimilation systems over their respective downscalers is greater in the 1.5km UKV than the 4km UK4 (to be confirmed).

- Extra high-resolution observation types not used in the global system gave mixed performance in the UK system, on occasion reducing the benefit of the full high-resolution DA system.

- MOPS cloud was identified as the main culprit for the weaker performance of the high-resolution observation family, and has since been replaced operationally by a combination of GeoCloud satellite cloud top data and surface cloud reports. But cloud assimilation remains a very challenging area.

- There is some evidence to assert that roughly a half of the benefit (in UK Index terms) of the UKV model relative to the global model over the first 12 hours of the forecast may be attributed to the high-resolution data assimilation system

- The most beneficial network for high-resolution DA appears to be the surface observation network, though on the period tested all the major observation categories (satellite, radar, conventional upper-air, aircraft) gave worthwhile benefit.

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7 Figures

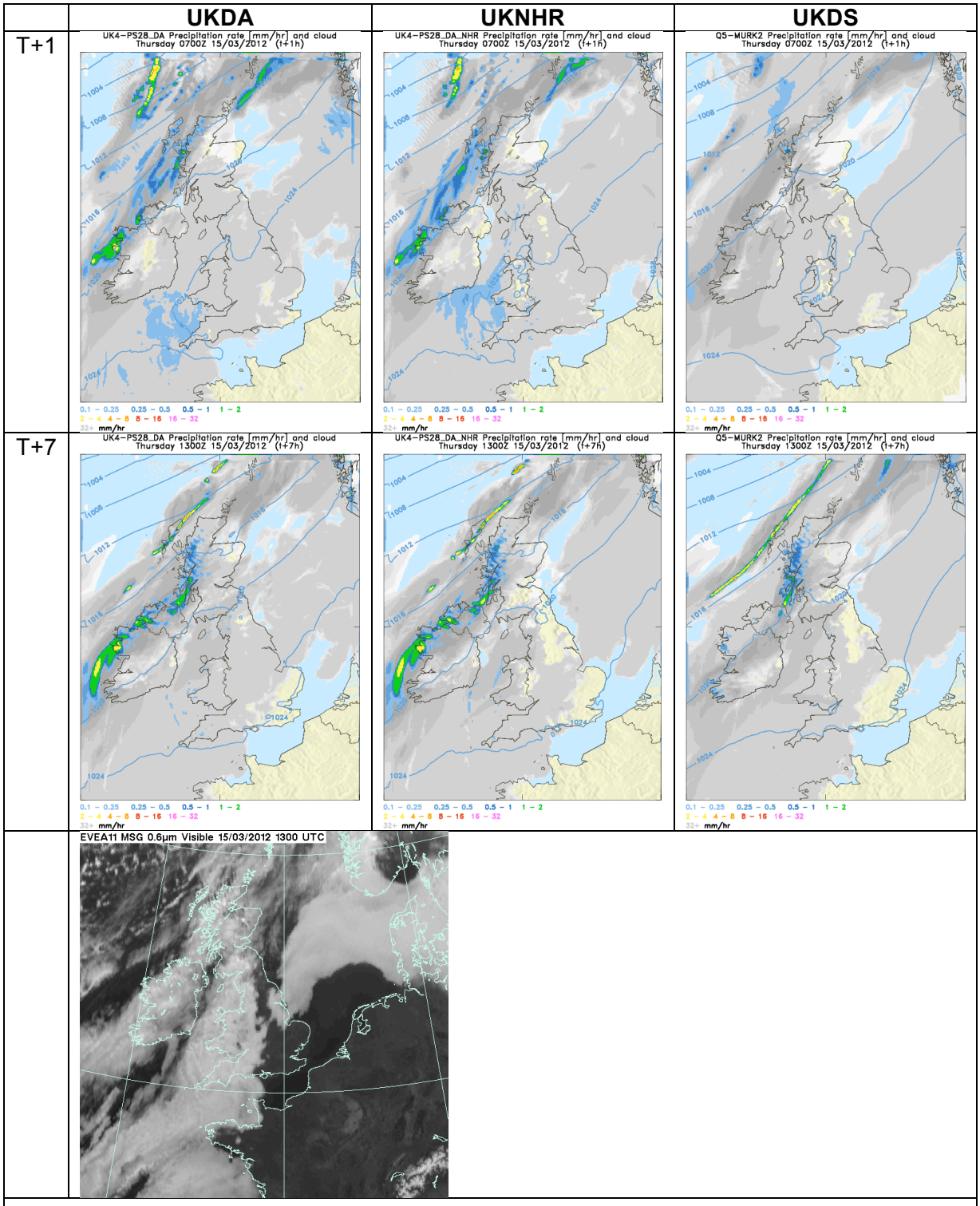

Figure 1 Cloud cover forecasts from three UK4 trial configurations at T+7 and T+1 during March 2012 stratocumulus episode, with verifying visible satellite image

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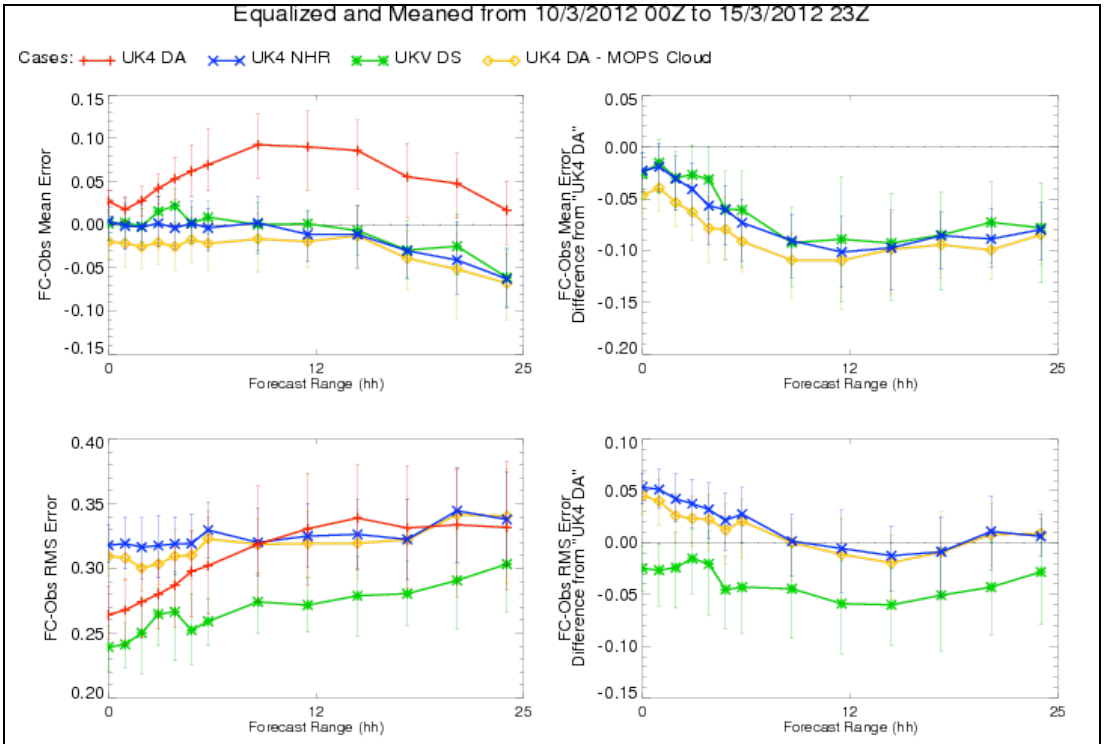

Figure 2 Cloud cover error (fraction) as a function of forecast time during March 2012 stratocumulus episode – bias (top), rms (bottom)

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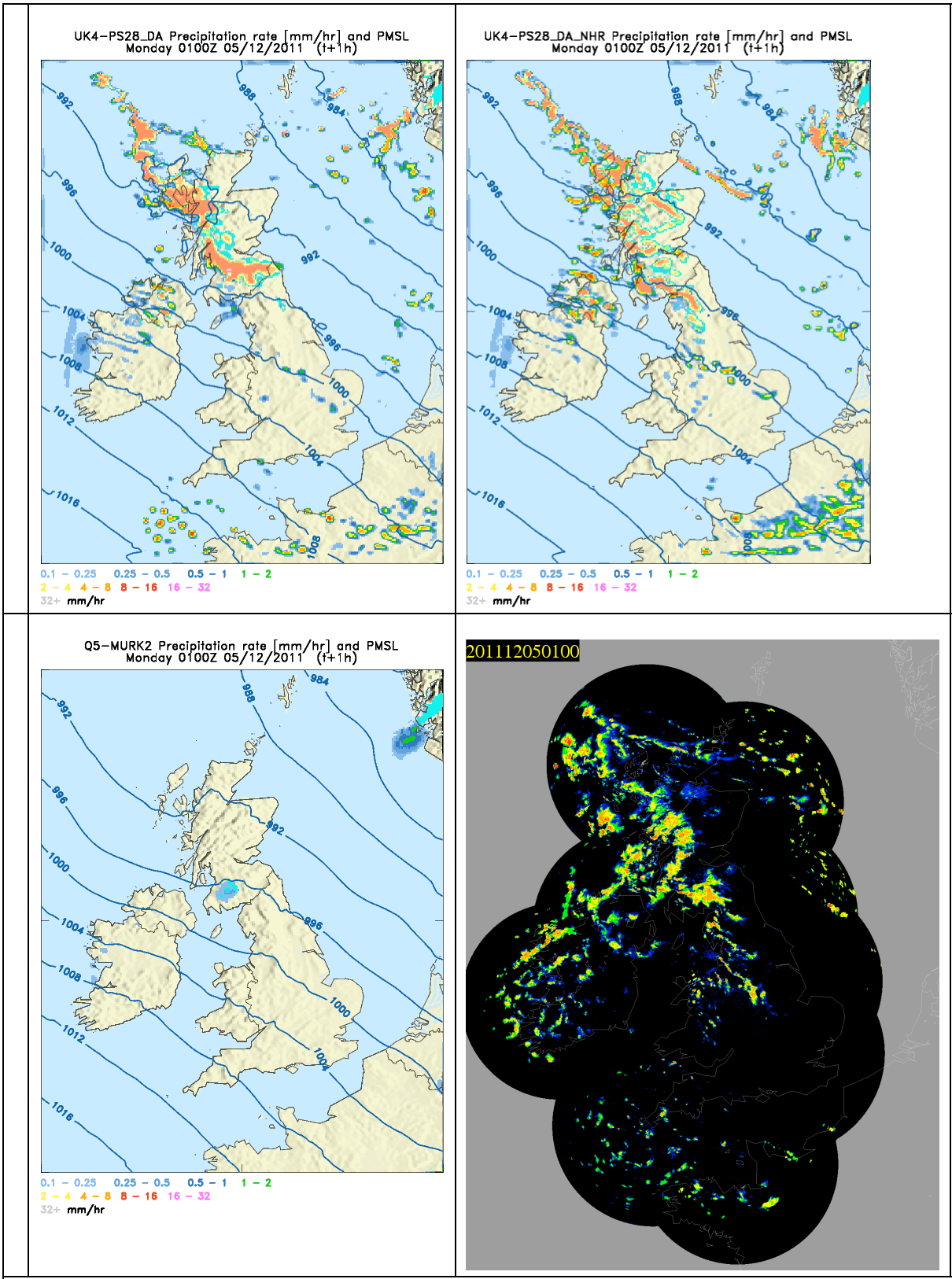

Figure 3 Precipitation forecasts from three UK4 trial configurations and T+1 in showery winter north-westerly. UKDA (top left), UKNHR (top right), and UKDS (bottom left), with radar frame (bottom right).

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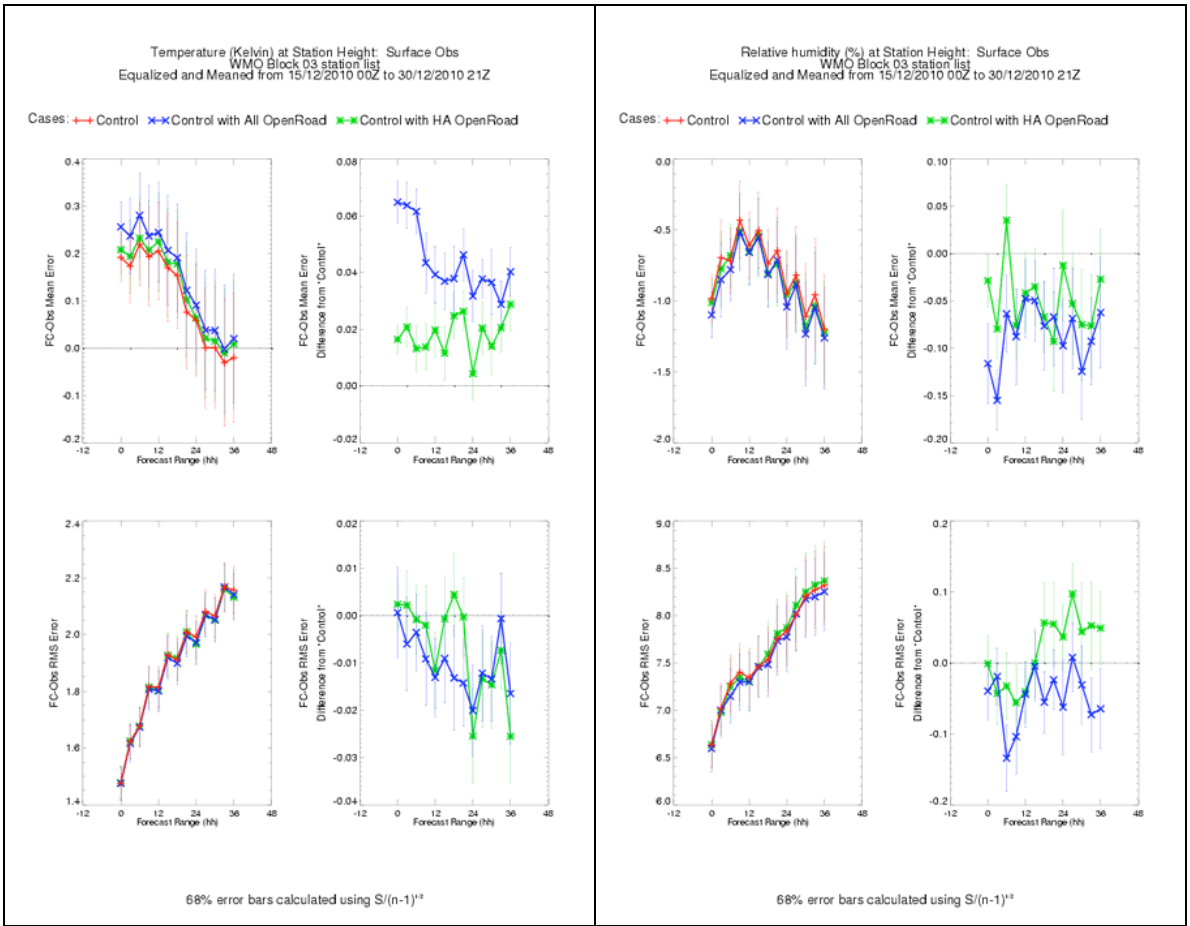

Figure 4 Screen temperature error (K) and Relative Humidity error (%) as a function of forecast time from two week winter trial with OpenRoad observations – bias (top), rms (bottom)

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Appendix 1 - UK4 Trial Scheme with Data Assimilation

The UK4 is a limited area implementation of the Met Office Unified model (Cullen and Davies, 1991), integrated on a 288 by 360 rotated latitude longitude grid having 0.036° resolution (approximately 4 km) and 70 vertical levels. The vertical grid is terrain following near the surface, evolving to constant pressure surfaces higher up. The top of the model is at 40km, and there are approximately 30 levels in the boundary layer. The dynamics time step is 100 seconds. Soil moisture and sea-surface temperatures (SST) are updated daily from the global soil moisture field and the Met Office's Operational Sea Surface Temperature Analysis (OSTIA) system (Donlon *et al*., 2011) respectively.

Lateral boundary conditions were derived from hourly output (every 3 hours for the earlier July 2011 trial) from the Unified Model run in global configuration on a˝ 1024 x 769 grid (~25km in mid-latitudes) and 70 levels, with a lid at roughly 80km. Both downscaler and DA runs use the latest global lbcs from t+0 onwards (eg 00 UTC cycle uses 00 UTC global lbcs from T+0 onwards). However, as the global lbc files only start at T+0, we need to use an older lbc file to cover the 2 hour pre-analysis assimilation period so that eg for a 00Z cycle, the period T-2 to T+0 uses the 18 UTC global lbcs.

Data assimilation is carried out using the Met Office 3DVAR with a 3-hour cycle and a First Guess at Appropriate Time (FGAT) scheme (Lorenc *et al.*, 2000). The analysis variables are stream function (ψ), velocity potential (χ), unbalanced pressure (A^p), and relative humidity (μ). The analysis grid resolution used is identical to that of the model, ie 4km. To damp fast gravity modes excited by the analysis and/or the interpolations required by the analysis, an incremental analysis update (IAU) procedure (Bloom *et al.*, 1996) is used whereby analysis increments are introduced $1/N^{th}$ at a time over N timesteps centred on the nominal analysis time.

Forecast error covariances in regional models are currently specified 'climatologically' through the so-called NMC method (Ingleby, 2001). These are computed from forecast differences between different runs of the regional model driven by the same boundary conditions – the 'lagged' NMC method. For the UK4 model, the input forecast fields are valid at T+12 and T+24 hours. Horizontal structure functions are represented by SOAR functions, the scale parameters being guided by statistics of observation-background differences for screen level data, following the method of Hollingsworth and Lönnberg (1986) with fixed values set for all vertical modes. In the UK models, the vertical structure functions are modified by the introduction of an adaptive vertical grid (Piccolo and Cullen, 2011 and Piccolo and Cullen, 2012) which effectively concentrates analysis resolution in regions with large static stability.

Observations assimilated in the UK4

Prior to assimilation, cloud data from both satellite and surface sources are pre-processed via the MOPS system (Macpherson *et al.*, 1996). The radar-based precipitation rate analysis is assimilated into the model using the technique of latent heat nudging (Jones and Macpherson, 1997 and Macpherson, 2001). A noteworthy feature is the variational assimilation of visibility observations in the higher resolution models (Clark *et al.*, 2008). The visibility observation operator is a highly nonlinear function of humidity, aerosol content and temperature.

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	00 UTC	03 UTC	06 UTC	09 UTC	12 UTC	15 UTC	18 UTC	21 UTC	Total
Surface	1693	1687	1728	1186	1811	1791	1795	1746	**13437**
Aircraft	66	55	698	480	908	584	1021	474	**4286**
Sonde/Profiler	48	39	43	25	53	46	45	44	**343**
Scatwind	0	0	0	0	104	0	0	128	**232**
Satwind	182	156	158	158	170	140	85	95	**1144**
SeviriClear	262	438	424	424	718	641	657	525	**4089**
DRW	617	622	373	373	12	257	58	0	**2312**
MOPS Cloud	34733	39923	43050	43050	49439	45526	46155	41716	**343592**
GNSS	220	214	220	0	219	212	220	219	**1524**
	37821	43134	46694	45696	53434	49197	50036	44947	370959
Obs Cut-off (mins)	186	81	151	31	186	82	186	81	

TABLE A1: Observation Totals for full UK high-resolution observing system – 22/11/2011

Table A1 above shows typical daily totals, broken down by DA cycle, for observations assimilated by the 3DVAR high-resolution DA system at the Met Office. It should be noted that the totals are for those observations actually assimilated; observations which for various reasons are rejected by the QC system are not included. The following characteristics are apparent:

- The diurnal variation in aircraft totals peaking at 18 UTC from a minimum at 03 UTC
- The scant availability of the Scatwind ob type
- The variability in Doppler Radial Wind (DRW) totals dictated largely by the presence or absence of precipitation
- The reduction in some observation types at the 09 UTC cycle due to the short observation cut-off time – indeed we lose GNSS altogether, which could have implications for an hourly cycle model with short cut-offs.
- Note that the Surface observation category includes visibility and OpenRoad observation subtypes, which for the purposes of this study have been classified as ‘high-resolution-only’ observation types, as they are not assimilated in the global model

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Appendix 2 – Brief history of the UK4 model

The UK4 km (UK4) project was triggered by the recommendations of May *et al.* (2004), following the strikingly good performance of the High Resolution Trial Model (HRTM) on the August 2004 flash flood event at Boscastle. Routine operational running of the UK4 began in autumn 2005, making the Met Office one of the first National Meteorological Services to have operational capability at such a resolution. The project was then extended to maintain and improve accuracy until being formally declared operational, i.e. providing data to operational systems. This happened in January 2008 when the OpenRoad road surface temperature forecasting system began to take input from the UK4 instead of the NAE.

An extension to the UK4 project was the development and transfer to operations of a convective-scale model (1.5km. gridlength) to be selected in different areas by demand of the Operations Centre, with a target date of December 2006. This was effectively a precursor to the operational implementation in 2010 of the UK 1.5km (UKV) variable grid convective-scale model covering the whole of the British Isles.

On their respective implementations, both the UK4 and UKV models took their lateral boundary forcing from the regional NAE model. However, trials of a 4km UK downscaler system starting from interpolated global analyses and driven by global model lateral boundary data showed benefit relative to the NAE-forced system, largely through superior upper-air verification of the global model relative to the NAE. Thus the UK models were switched from NAE to global lateral boundary data on 17th January 2012.

Increasing confidence in the performance of the high resolution models led to the UK4 replacing the NAE as supplier of UK NWP Index data from April 2011, which itself was superseded in this role by the UKV in January 2012. The UK4 was retired from operations on April 30th 2013.

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